
**Modeling the Distribution of Fish Eggs
in the Upper Water Column during the
Deepwater Horizon Oil Spill
Technical Report**

Prepared for:

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1. Introduction

Over the course of the *Deepwater Horizon* oil spill, fish eggs near the ocean surface were exposed to oil floating on the surface of the ocean, as well as oil entrained into the water as the result of turbulent mixing processes. The degree to which eggs were exposed to toxic concentrations of polycyclic aromatic hydrocarbons (PAHs) depended on the vertical distribution of these eggs relative to the distribution of oil. The vertical distribution of eggs in the upper water column is a function of the diameter and material density (i.e., buoyancy) of the eggs, and the upper ocean turbulence. Larger egg diameters and lower egg material densities both increase overall egg buoyancy and tend to increase the relative concentration of eggs near the surface, whereas a more turbulent upper ocean increases dispersion and tends to distribute eggs more evenly over the upper water column. To quantify the vertical distribution of eggs as a function of turbulence, egg diameter, and egg buoyancy, we used the VertEgg toolbox (Ådlandsvik, 2000), which solves equations for the steady-state egg distribution as a function of depth using relationships described by Sundby (1991, 1997) and others.

2. Model Inputs

2.1 Wind Speed and Dispersivity

In the surface-mixed layer of the upper ocean, turbulence (dispersivity) can be related to surface wind speed using the empirical relationship described by Sundby (1997):

$$K = (76.1 + 2.26W^2) \times 10^{-4}.$$

Here, K is dispersivity in m^2s^{-1} , and W is wind speed in $\text{m}\cdot\text{s}^{-1}$. We used this relationship to calculate the dispersivity beneath oil slicks in the Gulf of Mexico, as a function of wind speed. To evaluate the distribution of relevant wind speeds over areas of floating oil, we extracted North American Mesoscale (NAM) wind data (at 10 m above land surface) from all NAM grid cells that corresponded to the locations and dates where oil was present on the surface of the Gulf (NOAA, 2015). We used a three-day composite of the estimated extent of oil based on synthetic aperture radar (SAR) imagery (Graettinger et al., 2015), including oil coverage from each day of interest plus the oil coverage from the day before and day after. We then analyzed the wind in the NAM grid cells that intersected surface oil. Figure 1 summarizes the areal extent of oil and the NAM wind speeds underlying this analysis.

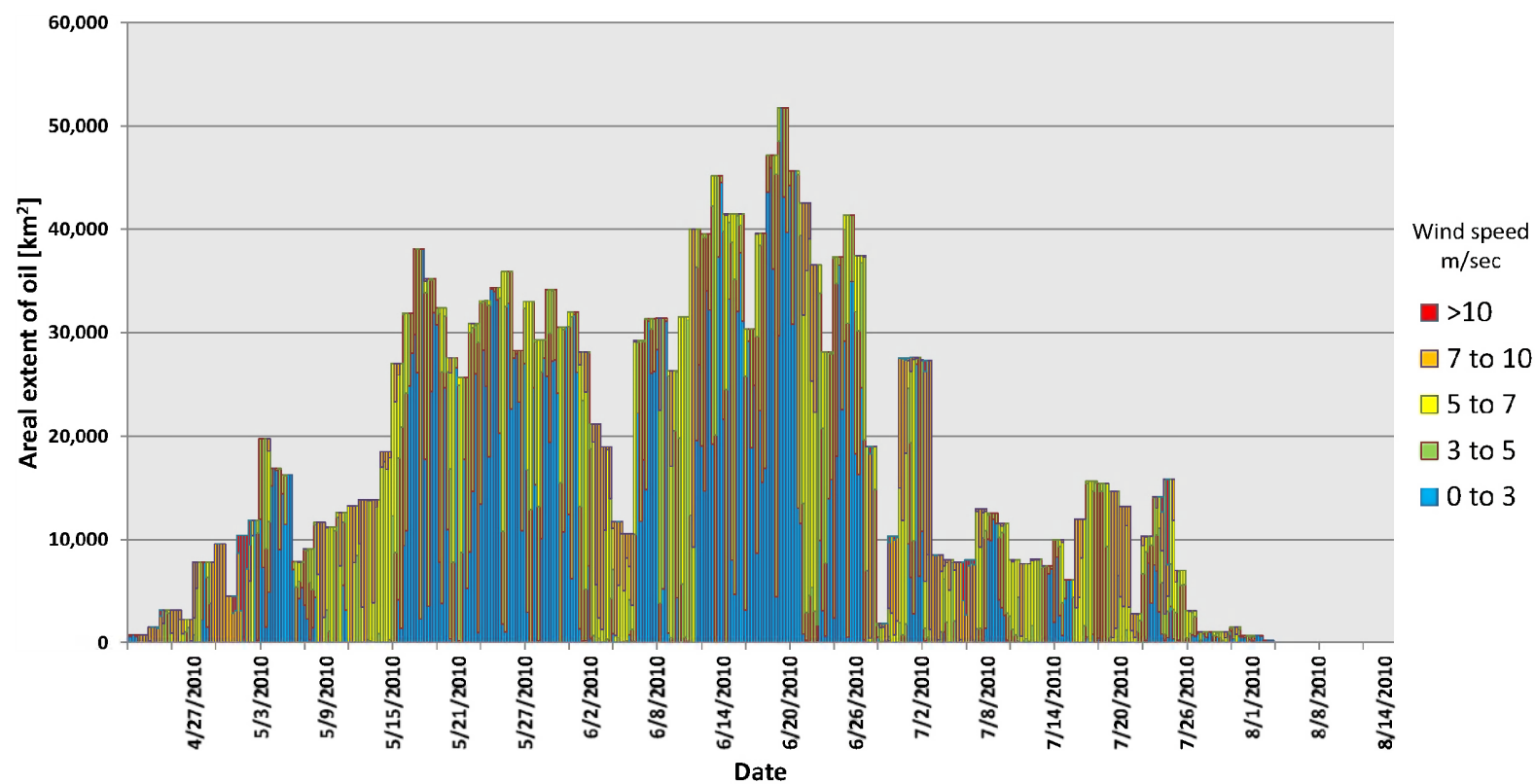


Figure 1. Area affected by six-hour average wind speeds ($\text{m}\cdot\text{s}^{-1}$) over floating oil during the *Deepwater Horizon* oil spill.

We weighted the distribution of wind speeds by the relative area of surface oil within each grid cell, so that wind speeds from NAM cells that were fully covered by oil were weighted more heavily than wind speeds from NAM cells with only fractional coverage (Figure 2). To evaluate wind speeds over oil that covered estuarine waters, we used wind speeds measured at the Grand Isle station GISL1 – 8761724 (National Data Buoy Center, 2015) from May 1 to August 11, 2010, because this is the closest station to the estuarine waters where the majority of surface oiling occurred. Dispersivity was then assumed to scale with wind speed using the relationship described above.

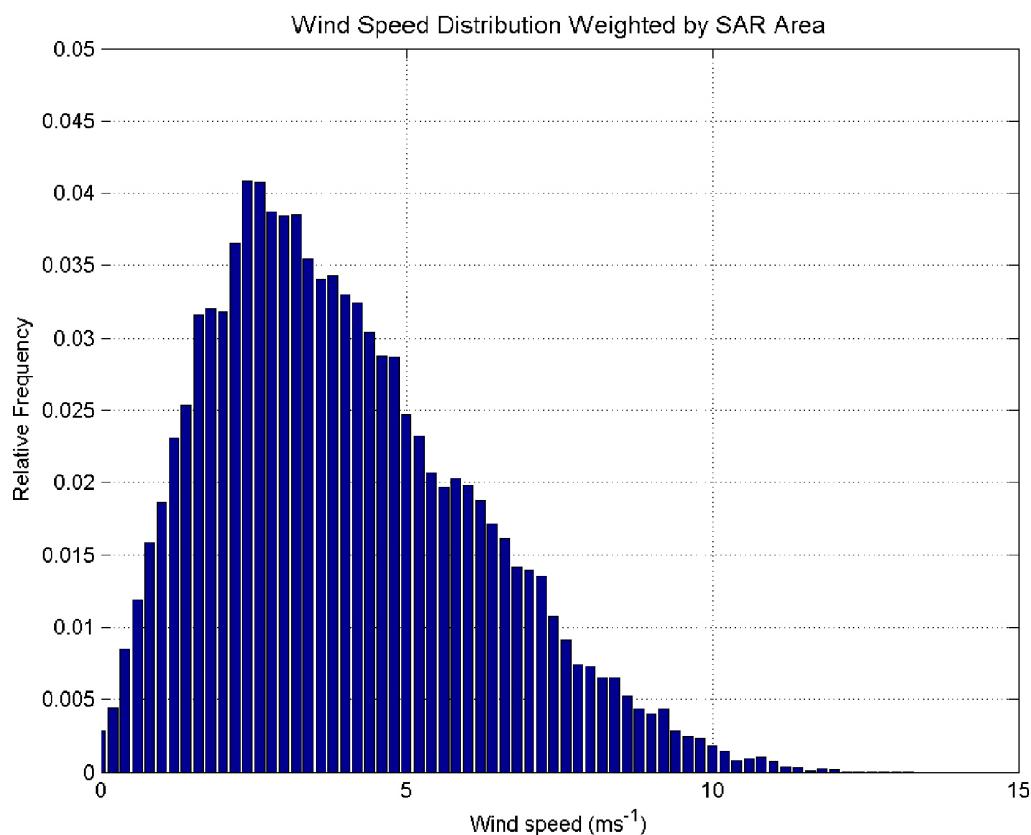


Figure 2. Sample of wind speeds over surface oil used as input to the VertEgg model. NAM grid cells with higher percent oil coverage according to SAR were weighted more heavily than cells with lower percent oil coverage.

2.2 Egg Buoyancy

A number of studies have been conducted on various marine species to determine relative egg buoyancy ($\Delta\rho$), which is the difference between the specific gravity of the water (ρ_w) and the specific gravity of the egg (ρ_e). Jung et al. (2014) reported that the typical $\Delta\rho$ for pelagic eggs ranged from 1 to 3 kg/m³. Goarant et al. (2007) found that European anchovy (*Engraulis encrasicolus*) eggs that were spawned in denser, more saline water in the Bay of Biscay had higher absolute densities, whereas eggs that were spawned in the less dense, fresher waters of the bay had lower absolute densities. However, these eggs remained positively buoyant across a range of salinities, with an average $\Delta\rho$ of 0.7 kg/m³.

To supplement the information available in the literature, and to ensure that we had data from species in the Gulf of Mexico, we conducted a series of laboratory experiments to measure egg buoyancy. The methods described here were for tests using eggs from red drum (*Sciaenops ocellatus*), mahi-mahi (*Coryphaena hippurus*), and bay anchovy (*Anchoa mitchilli*). We conducted these test at three different facilities using similar methods.

We obtained red drum eggs from the Sea Center Texas (Texas Parks and Wildlife) in Lake Jackson, Texas; mahi-mahi eggs from the Rosenstiel School of Marine and Atmospheric Science (RSMAS) at the University of Miami; and bay anchovy eggs from the Louisiana Universities Marine Consortium (LUMCON) in Cocodrie, Louisiana. The buoyancy tests were conducted at the same facilities that produced the eggs. We collected red drum eggs directly from spawning tanks 2–4 hours post fertilization (hpf) and from incubator tanks at 10–14 hpf; mahi-mahi eggs were collected from spawning tanks at 6–8 hpf; and bay anchovy eggs were collected from spawning tanks at 12 hpf. We conducted experiments with eggs immediately after collection. Depending on the collection time, experiments were conducted on eggs that were in different stages of embryonic development. To put the timing of the testing in context with overall embryonic development for each species, the total developmental time from fertilization to hatching for each species was as follows: (1) red drum and bay anchovy embryos typically hatch at approximately 20–24 hpf, and (2) mahi-mahi typically hatch at 36–40 hpf.

The methods used for all of the egg buoyancy experiments were the same: we placed eggs into 500-mL beakers containing water with varying densities and determined the density of the eggs based on the density of the water in which they were found to be neutrally buoyant. Waters with different densities were generated by varying the salinity of each beaker using two stocks of water. The first stock was pure reverse-osmosis (RO) water. The second was RO water that we combined with an Instant Ocean sea salt mix to produce a stock of approximately 50 millisiemens (mS). Using these two stock waters, we were able to produce water along a salinity gradient. We measured salinity using a Pinpoint® salinity monitor and then converted the reading from mS to parts per thousand (ppt) using the conversion chart provided with the monitor (American Marine, 1992).

We carried out initial tests with 5 ppt salinity splits between treatments to determine the approximate salinity where all eggs either floated or sank. Once we had determined those bounding salinity values, we produced salinity treatments at approximately 1 ppt splits between those two end members. We placed between 30 and 60 embryos into the middle of the water column in each beaker using a plastic pipette and then let them settle for 5 minutes before determining the approximate percentage of embryos that were either floating, neutrally buoyant, or had sunk to the bottom of the beaker.

Once we determined the salinity at which a majority of the eggs were neutrally buoyant, we used the density of that solution as a proxy for ρ_e . We determined the density of the water from salinity and temperature, using an online calculator that summarized the relationships described by El-Dessouky and Ettouney (2002).¹ We then determined the buoyancy $\Delta\rho$ of the eggs by subtracting ρ_e from the density of the brood tank water.

Based on these experiments, $\Delta\rho$ for the three species tested ranged from 1.31 to 2.98 kg/m³ (Table 1), consistent with the 1–3 kg/m³ values reported by Jung et al. (2014). As input to our model, we assumed a uniform distribution of egg buoyancies between 1.3 and 3.0 kg/m³.

Table 1. Average egg buoyancy and diameters measured in the laboratory as part of the Trustees' *Deepwater Horizon* Natural Resource Damage Assessment (NRDA) Toxicity Testing program

| Species | Buoyancy | | Diameter (mm) | | |
|-------------|-----------------|----------------|---------------|------|----------------|
| | $\Delta\rho$ | n ^a | Average | SD | n ^b |
| Red drum | 1.31–2.80 | 4 | 1.05 | 0.08 | 32 |
| Mahi-mahi | 1.50–2.40 | 2 | 1.41 | 0.03 | 40 |
| Bay anchovy | 2.98 | 1 | 0.84 | 0.04 | 60 |
| Red snapper | NA ^c | NA | 0.81 | 0.05 | 60 |

a. Number of tests conducted.

b. Number of embryos measured.

c. Test not conducted.

1. http://www.ifh.uni-karlsruhe.de/science/envflu/research/brinedis/density&viscosity_calculator.xls.

2.3 Egg Diameter

Pauly and Pullin (1988) synthesized literature on fish egg diameters from a wide range of fish species. We extracted egg diameter data for species present in the Gulf of Mexico, yielding a mean diameter of 1.04 mm and a standard deviation of 0.19 mm (Table 2). This range was consistent with an independent compilation of egg-diameter values from the literature for selected Gulf of Mexico species (Gearon et al., 2015). The Gearon et al. (2015) dataset indicated an average diameter of 1.2 mm and a standard deviation of 0.4 mm.

Table 2. Egg diameters for species present in the Gulf of Mexico (modified from Pauly and Pullin, 1988)

| Family | Species | Days | Diameter (mm) | Temperature (°C) |
|---------------------------|------------------------------------|------|---------------|------------------|
| Clupeidae | <i>Etrumeus teres</i> | 1.50 | 1.33 | 20.5 |
| Merluccidae | <i>Merluccius albidus</i> | 7.00 | 1.10 | 9.8 |
| | <i>Prionotus carolinus</i> | 2.50 | 1.05 | 22.0 |
| Pomatomidae | <i>Pomatomus saltatrix</i> | 1.96 | 1.00 | 20.0 |
| Coryphaenidae | <i>Coryphaena hippurus</i> | 2.00 | 1.40 | 24.5 |
| Sparidae | <i>Stenotomus chrysop</i> | 1.67 | 1.00 | 22.0 |
| | <i>Archosargus probatocephalus</i> | 1.67 | 0.80 | 25.5 |
| Sciaenidae | <i>Bairdiella chrysoura</i> | 0.75 | 0.76 | 27.0 |
| | <i>Menticirrhus saxatilis</i> | 2.00 | 0.82 | 20.5 |
| | <i>Lagodon rhomboides</i> | 2.00 | 1.02 | 18.0 |
| Ephippidae | <i>Chaetodipterus faber</i> | 1.00 | 1.00 | 27.0 |
| Mugilidae | <i>Mugil cephalus</i> | 1.54 | 0.93 | 24.0 |
| Scombridae | <i>Scomber scomber</i> | 7.38 | 1.19 | 7.4 |
| | <i>Thunnus albacares</i> | 1.85 | 0.96 | 18.7 |
| | <i>Thunnus obesus</i> | 0.88 | 1.05 | 28.8 |
| | <i>Katsuwonus pelamis</i> | 1.10 | 1.00 | 26.7 |
| | <i>Scomberomorus maculatus</i> | 1.04 | 1.03 | 25.0 |
| Stromateidae | <i>Peprilus triacanthus</i> | 3.00 | 0.75 | 14.6 |
| Bothidae | <i>Paralichthys dentatus</i> | 2.33 | 1.02 | 22.9 |
| Ostraciidae | <i>Lactophrys quadricornis</i> | 2.00 | 1.46 | 27.3 |
| Mean diameter | | | 1.04 | |
| Standard deviation | | | 0.19 | |

We also measured red drum, mahi-mahi, bay anchovy, and red snapper egg diameters in the laboratory using a microscope and stage micrometer. These measurements were made in conjunction with buoyancy testing at each respective facility described above for these fish species (LUMCON collected the red snapper measurements). The average egg diameters for these species ranged from 0.8 to 1.4 mm (Table 1).

Because all of the estimates of egg diameters were generally in agreement, we used the Gulf of Mexico subset of Pauly and Pullin (1988), described above and shown in Table 2, as the input for our egg diameters in the VertEgg model. We generated a pseudorandom normal distribution of diameters with a mean of 1.04 mm and a standard deviation of 0.19 mm.

3. Model Results

For each input parameter set of egg buoyancy, egg diameter, and dispersivity, the VertEgg toolbox generated a steady-state profile illustrating how fish eggs were distributed through the upper water column. We applied a Monte Carlo statistical method (Robert and Casella, 1999) to evaluate the range of model outputs from the distribution of input parameters. We used 1,000 parameter sets, selected randomly from the input distributions of wind speed, density, and diameter described above, to generate 1,000 steady-state profiles of the relative concentration of fish eggs in the upper water column. We used these 1,000 profiles to generate a statistical probability distribution of eggs with depth. We created one set of solutions to represent the egg distribution in the upper 20 m of the water column for offshore waters (Figure 3a), and a second set of solutions to represent egg distributions in shallow estuarine waters (Figure 3b). We used 2.5 m as an average depth for shallow estuarine waters; this is an approximate regional average of depths from the estuaries and bays that contained oil at some time during the oil spill (Table 3).

The model domain in the offshore waters was selected to represent the depth of the upper, mixed layer of the water column. Conductivity, temperature, and depth (CTD) data were collected during many of the cruises over the course of the *Deepwater Horizon* oil spill. Analysis of these data demonstrated that the mixed layer depth was variable and was influenced by a balance of stratifying forces and perturbation forces. Wind and wave action caused mixing of the water column, and periods with low wind and small waves, as well as strong solar insolation, allowed the water to stratify, resulting in shallower mixed layers (Grennan et al., 2014). The average depth of the upper mixed layer in the vicinity of the *Deepwater Horizon* spill site was approximately 16 m, but extended to depths of 29 m at some times (Grennan et al., 2014). In addition, we found that PAH concentrations (and other evidence of oil) were either not detectable, or were detectable only at low concentrations (i.e., total PAH at or below 1 µg/L) below depths of 20 m (see Travers et al., 2015a). Based on these observations, we simulated the egg distribution over a vertical depth of 20 m for our offshore modeling, and did not model egg distributions or TPAH50 exposure below 20-m depth (see Travers et al., 2015b).

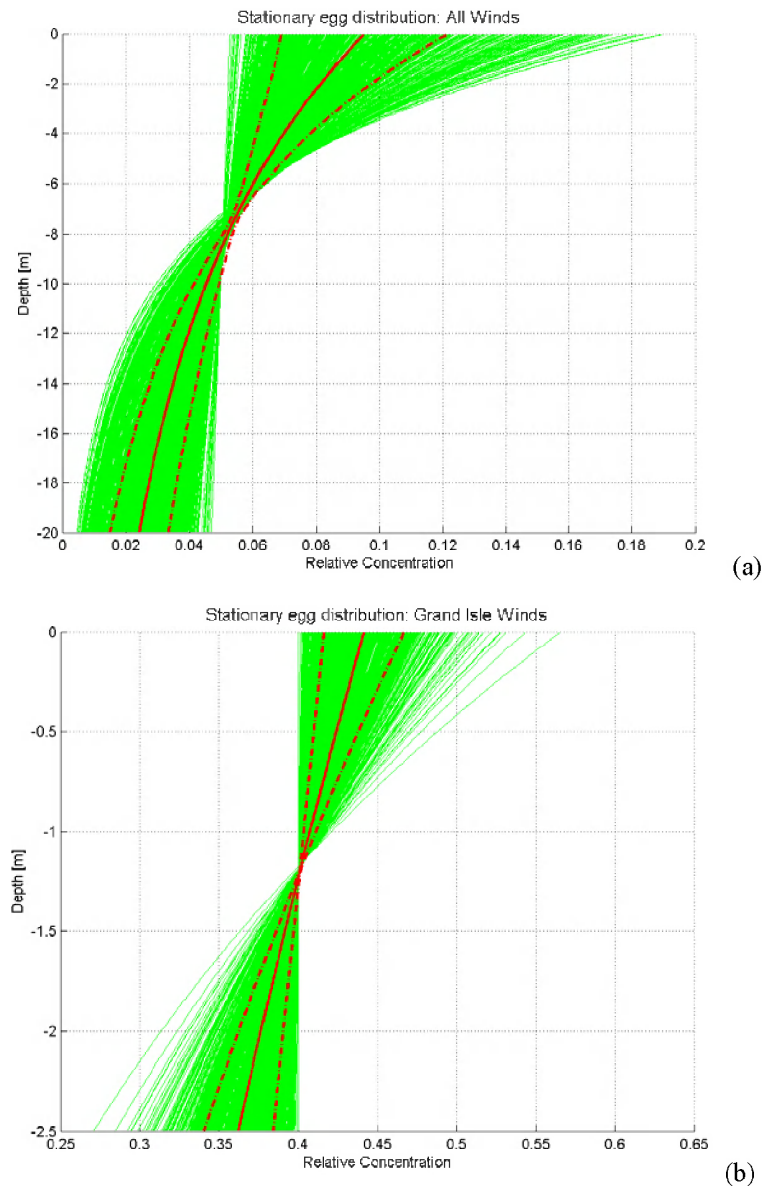


Figure 3. Sample output showing vertical distribution of eggs for 1,000 randomly selected combinations of wind speed, egg buoyancy ($\Delta\rho$), and egg diameter. (a) Relative vertical distribution of eggs over a 20-m, upper mixed zone in offshore waters. The green lines represent 1,000 VertEgg solutions, each for a single set of values for wind speed, egg buoyancy, and egg diameter. The solid line represents the mean of these 1,000 iterations, and the dashed lines are $\pm 1\sigma$. (b) Relative vertical distribution of eggs over a 2.5-m water column in estuarine waters. Line colors same as in Figure 3a.

Table 3. Average depths for estuarine waters that contained a surface oil slick at some point during the spill

| Estuary/bay | Average depth (m) |
|--|-------------------|
| Barataria Bay | 2 |
| Timbalier-Terrebonne | 2 |
| Breton and Chandeleur Sounds | 3 |
| Mississippi Sound | 4 |
| Mobile Bay | 3 |
| Sources: Values from GulfBase.org (2015), citing USFWS (1982) and U.S. EPA (1999). | |

3.1 Sensitivity Analysis

The contributions to changes in the vertical distribution of eggs from uncertainties in egg diameter, egg buoyancy, and wind speed are all encompassed by our Monte Carlo simulation. However, to evaluate the sensitivity of the modeled egg distribution to our estimates of density and diameter, we ran the VertEgg model using the mean, plus or minus one standard deviation for diameter, and using the upper and lower limits of $\Delta\rho$ from our laboratory and literature-based distributions. The contributions to changes in the vertical distribution of eggs from uncertainty in egg density and egg diameter are similar (Figure 4).

4. Summary

Spatial and temporal differences in egg buoyancy, egg diameter, and wind speed yield differences in the exact vertical distribution of eggs during the *Deepwater Horizon* oil spill. However, across this range of parameter space, model simulations using the VertEgg model demonstrate that (1) fish eggs in the upper mixed zone (~ 20 m) of the open ocean were concentrated near the surface relative to the base of the upper mixed zone, and (2) fish eggs in estuarine waters were more evenly distributed with depth, but still had a tendency to be concentrated more toward the surface relative to the base of the water column. These modeled egg distributions provided the inputs for an egg exposure model, in which fish egg distributions were intersected with measured distributions of PAHs and ultraviolet radiation to estimate the toxicity of the *Deepwater Horizon* event to fish eggs in the Gulf of Mexico (Travers et al., 2015b).

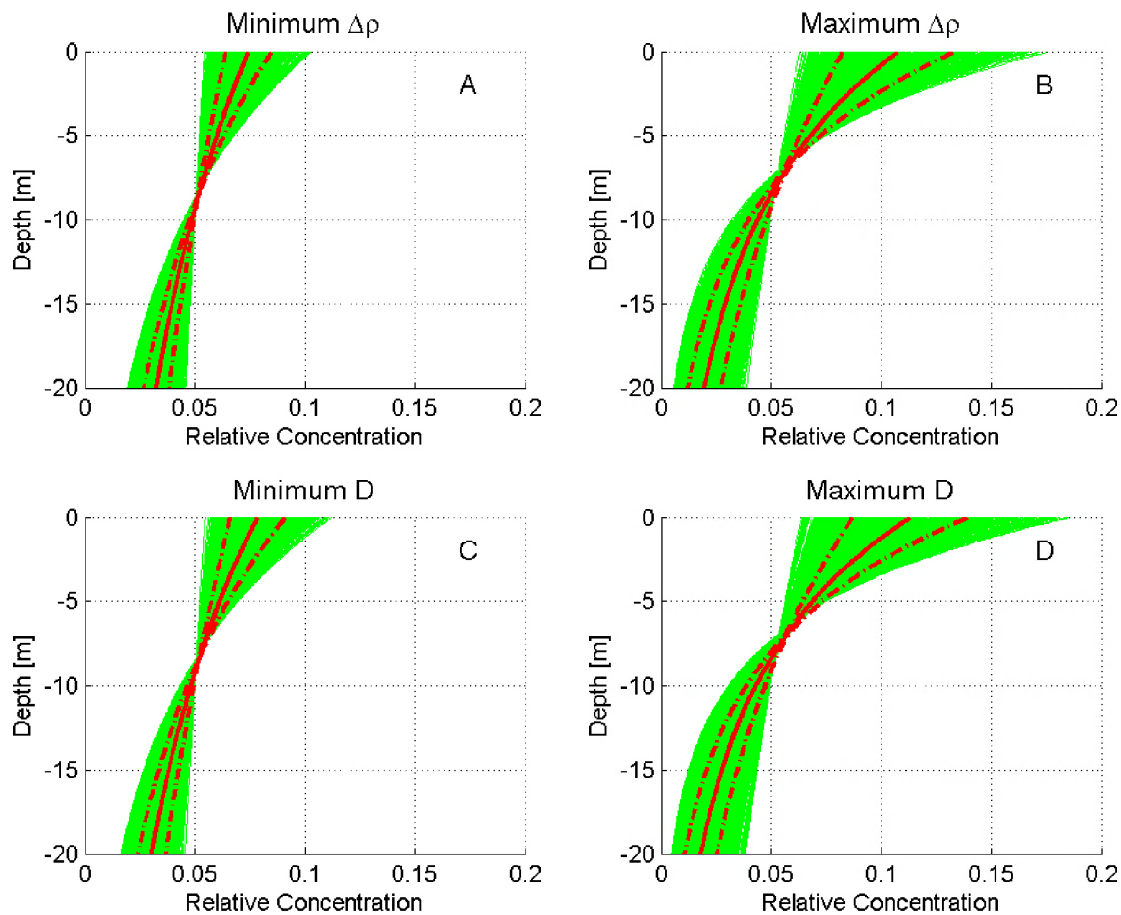


Figure 4. Sensitivity analysis illustrating the changes in the modeled distribution of eggs when assumptions for egg density ($\Delta\rho$) and diameter (D) are changed. “Minimum” and “maximum” plots represent model runs where the parameter noted was held constant, and the other parameters were allowed to vary. Fixed parameter values are as follows (see text for references and description of ranges): (A) $\Delta\rho = 1.3 \text{ kg/m}^3$, (B) $\Delta\rho = 3.0 \text{ kg/m}^3$, (C) $D = 0.85 \text{ mm}$, and (D) $D = 1.25 \text{ mm}$. Line colors same as Figures 3a–b.

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